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ESTIMATION OF PHOSPHORUS FLUX IN A REGULATED CHANNEL

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Abstract—During a nutrient loading study in the Okanagan River Basin, British Columbia, the regression relationship between phosphorus concentration and the Okanagan River discharge was shown to be not statistically significant. Phosphorus flux could, therefore, not be determined by conventional methods which rely on the concentration–discharge relationship. The reason for failure of conventional methods is the regulated nature of the Okanagan River flow. Two sampling strategies for chemical analysis of water samples were applied: (a) simultaneous, based on manual collection of sample replicates; and (b) sequential, using an automatic device to obtain a series of point concentration measurements. These sampling strategies provided a basis for nutrient flux estimation by the following methods: (a) partial load method, resulting from simultaneous sampling; and (b) flow interval method, based on sequential sampling. Load estimates and their confidence limits derived from the partial load method were compared with loads obtained by the flow interval method. There was a high level of correlation between the load estimates. Annual trends are more appropriately investigated by the flow interval method, cross-sectional load variability and confidence limits should be assessed by the partial load method.

Key words—phosphorus flux, Okanagan River, water quality sampling

INTRODUCTION

Problem and objectives

Water quality conditions in the Okanagan Basin lakes of British Columbia, Canada present a challenge to water managers. A previous nutrient loading study (Canada–British Columbia Okanagan Basin Agreement, 1974), indicated phosphorus as one of the major nutrients promoting eutrophication of these lakes. In 1976, Canada and British Columbia entered into a 5-year agreement to implement a comprehensive framework plan for the development and management of water resources in the Okanagan River Basin (Report on the Okanagan Basin Implementation Agreement, 1982). Under this agreement, a new nutrient loading study was carried out by Water Quality Branch, Pacific and Yukon Region, Vancouver, B.C. in the southern part of the Okanagan River basin (Fig. 1).

The major activities affecting water quality in this part of the basin are urban developments, particularly in Penticton, and rural developments adjacent to the lakes in the valley. Phosphorus removal from the Penticton waste water treatment plant began in 1971 with the aim of reducing loads of this nutrient to receiving waters.

In comparing nutrient load estimates from the previous study (Canada–British Columbia Okanagan Basin Agreement, 1974) with those obtained in 1976, it was demonstrated that no general trends of nutrient loads could be established. Reasons for the uncertain trend information were: (a) an inadequate earlier sampling strategy resulting in the calculation of the annual mean load estimates without known precision levels and (b) the increasing input of phosphorus to the lakes from non-point sources counterbalancing the effects of phosphorus reduction from point sources. As a result, the purpose of the present article is to address (a) the question of appropriate sampling strategies and (b) methods for estimating phosphorus loads with known precision.

BACKGROUND

The transport of dissolved constituents is related to many factors of which volume of water is normally the most significant (Ledbetter and Gloyna, 1964; Steele, 1968). The discharge–concentration relationship is often determined through regression techniques using linear, exponential or logarithmic expressions. Johnson *et al.* (1969) employed a hyperbolic function and Hem (1970) discussed broad features of empirical models. Hall (1971) identified six commonly used statistical models, based on assumptions that rarely occur in nature. Johnson (1979) described various procedures for phosphorus transport determination by using either regression of phosphorus concentration on discharge or collection of grab samples, distributed over the range of stream discharge, with several combinations of weighting procedures and sampling schedules. Statistically significant relationships between discharge and total

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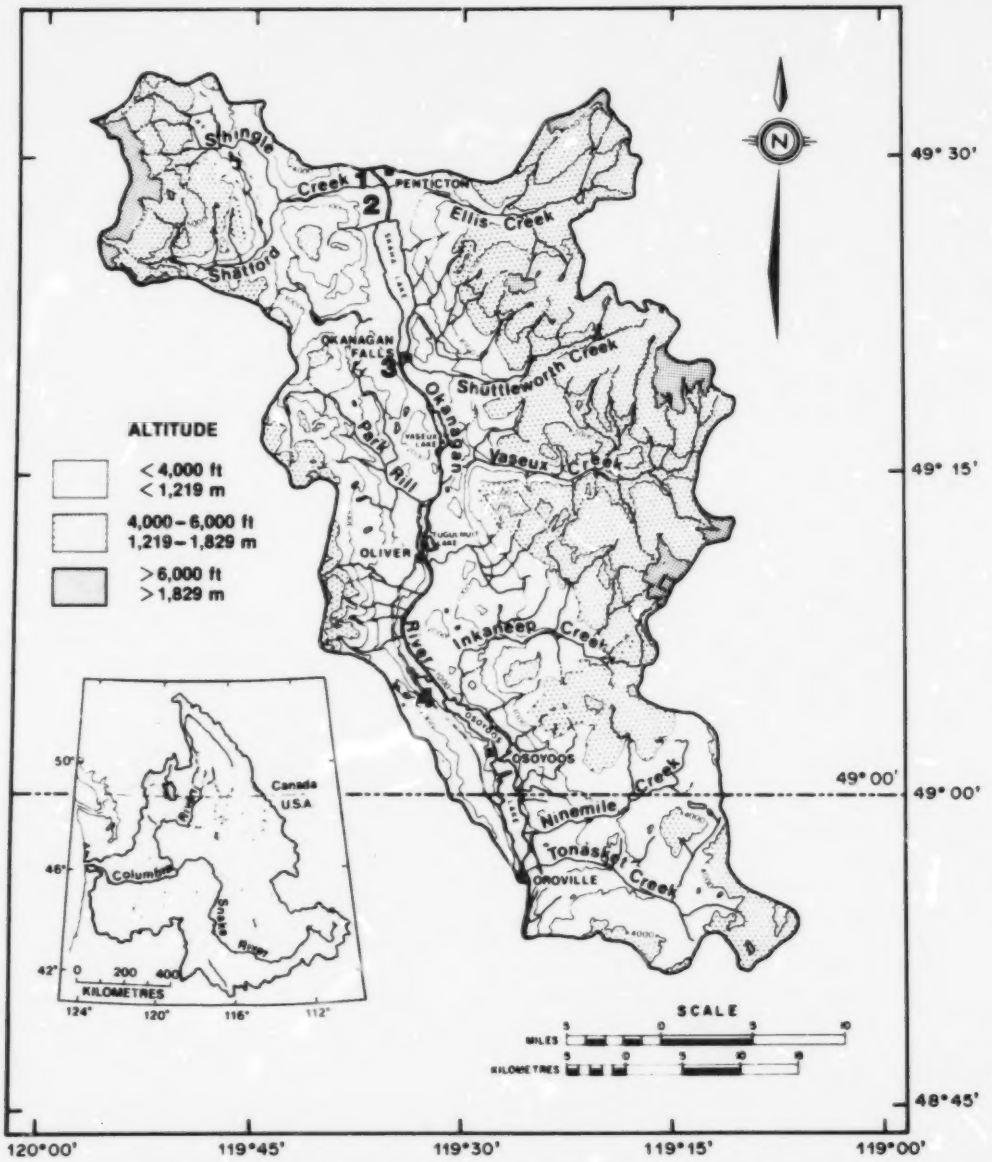

Fig. 1. Southern part of the Okanagan River Basin. Hydrometric stations (1, 3 and 4) and water quality sampling sites (1, 2, 3 and 4).

phosphorus concentration have been found by Keup (1968) in many river systems. Wang and Evans (1970) found inverse relationships between discharge and concentration of orthophosphate. Some studies indicate that total phosphorus concentration increases faster than the river flow, reaching its maximum before a peak flow and then declines more rapidly than the rate of flow (Cahill *et al.*, 1974). During the present study, however the concentration–discharge relationship was not found statistically significant (Zeman *et al.*, 1977) because the flow in the Okanagan River is regulated.

The major portion of phosphorus transport in streams occurs during high flow (Ryden *et al.*, 1973) because most of the total phosphorus which is attached to particles suspended in the stream or deposited on stream beds, comes from eroded soil after snowmelt or during storm run-off. Total phosphorus which is stored on stream beds is liable to be resuspended, and because of turbulence, transported in periods of high flow. Thus concentration of phosphorus is subject to significant temporal variation and spatial variation across the channel. Most of the procedures dealing with transport of chemical constituents in stream water are oriented towards the determination of temporal variation of load esti-

mates. These estimates are derived usually from single grab samples or from sequential point samples. Such techniques do not provide information on spatial heterogeneity of concentration measurements in the channel cross-sections. Although this information is essential in calculating confidence limits of load estimates, little attention has been paid to the problem. The procedures undertaken during this study in the Okanagan River are based on sampling strategies in a regulated channel (Zeman, 1982) which allow the estimation of phosphorus loads with known precision.

Phosphorus found in receiving waters is classified into various components according to the available analytical methods (Stumm and Morgan, 1970). In this study and many nutrient loading studies, phosphorus is differentiated into total phosphorus and dissolved phosphorus forms. Vollenweider (1971) considers total phosphorus concentrations of 10 and 20 mg m^{-3} to be the transition range between oligotrophy and eutrophy of lakes. The approach relating the surface loads of total phosphorus to the mean depth/hydraulic residence time is used by some workers in estimating the degree of eutrophication of aquatic ecosystems (Rast and Lee, 1978).

STUDY AREA

The topographic map (Fig. 1) shows the location of the southern Okanagan Basin, British Columbia. Okanagan River flows from Okanagan Lake through Skaha, Vaseux and Osoyoos Lakes to the Canada–U.S.A. border.

In 1976, the reach of the Okanagan River channel linking Okanagan and Skaha Lakes was subjected to a preliminary study of nutrient mixing (Zeman *et al.*, 1977). Then, the monitoring program of nutrient transport conducted during the period from 1976 to 1980 included the Okanagan River, Skaha Lake and the Okanagan River–Osoyoos Lakes sub-systems.

The amounts of phosphorus loads carried by the Okanagan River can be related to the following sources: (a) allochthonous nutrient inputs from Okanagan Lake, Ellis Creek, Shingle Creek, Penticton and Oliver waste treatment plants, diffuse sources and direct bulk fallout from the atmosphere; and (b) autochthonous nutrient exchanges in the form of turbulent mixing in vertical, lateral and downstream directions, bed and bank erosion, sediment and nutrient entrainment, chemical precipitation and absorption of nutrients and organic sedimentation.

MEASUREMENTS

Sampling strategies

Two sampling strategies, the simultaneous and sequential strategies were used for collection of samples for chemical analysis. These strategies were described by Zeman *et al.* (1977) in detail. The simultaneous strategy, employing a manual sampler, enabled collection of six sample replicates at a number of points across the channel. This strategy provided the possibility of calculating confidence limits around the point concentration measurements. The sequential sampling strategy, employing a portable discrete sampling device, was used to obtain time series records of concentration measurements, taken at a single point, approximately at 0.6 of the depth of water and at 0.5 of the channel width.

Frequency of sampling

The simultaneous sampling strategy was used once a day during a preliminary study of nutrient dispersion, in December 1976. During the 4-year monitoring program, this strategy was applied once a month with the aim of comparing results of measurements derived from sequential sampling strategy. The sequential sampling was carried out on two consecutive, randomly chosen days within each week. Time of sampling was at 03:00, 09:00, 15:00 and 21:00 h. This sampling scheme was based on the statistically significant diurnal variation, determined during the preliminary study.

Chemical analysis

Samples collected for the dissolved phosphorus analyses were filtered immediately after their collection through the pre-soaked and prewashed 0.45 μm cellulose acetate membrane filter of 47 mm dia. The method (Murphy and Riley, 1962) which differentiates phosphorus in water samples as total phosphorus and dissolved phosphorus was used for chemical analysis. Results were reported as total phosphorus (P) and total dissolved phosphorus (P) in mg l^{-1}.

LOAD DETERMINATION

Two procedures, the partial load and the flow interval methods were used to estimate total phosphorus (P) and total dissolved phosphorus (P) loads.

Partial load method

The algorithm for the partial load method was described by Zeman and Slaymaker (1981). This method was based on the combined hydrometric and simultaneous concentration measurements in the channel cross-sections. The method consisted of the calculation of loads, and their 95% confidence limits, in four slices (flow parcels) into which the channel was divided. The sum of these partial loads resulted in the estimation of total load, with 95% confidence limits, passing through the channel cross-section. Further, the magnitude and precision of lateral and vertical variation of loads in the channel cross-sections was assessed by this method. This assessment was used for the selection of sampling sites in the preliminary study, (Zeman *et al.*, 1977) and for the comparison of loads estimated by flow interval method, described below.

Flow interval method

Phosphorus load determination by the flow interval method is based on hourly discharge data and sequential sampling for chemical analysis. The hourly discharge data are used to divide sampling days into four equal time intervals and time of sampling is scheduled in the middle of each interval.

Discharge for flow interval

The discharge for a flow interval is calculated from the original discharge data ($m^3 s^{-1}$) and cumulated over the 6 h interval which encompasses the time of chemical sampling. The procedure can be described by the following mathematical expression:

$$Q_m = t_c \sum_{r}^{z} q_n$$

where:

Q_m = the cumulative discharge for the 6-h flow interval in m^3, and $m = 1, \ldots, 4$,
q_n = the hourly discharge expressed in $m^3 h^{-1}$, and $n = 1, \ldots, 24$,
t_c = the constant for conversion of discharge from $m^3 s^{-1}$ to hourly discharge in $m^3 h^{-1}$,
r = the lower time limit of a flow interval, $r = (m - 1)6$,
z = the upper time limit of a flow interval, $z = (m - 1)6 + 5$.

This discharge, multiplied by nutrient concentration measured in the middle of each flow interval (03:00, 09:00, 15:00 and 21:00 h, respectively) gives nutrient load, expressed in kg per 6 h flow interval. The sum of the loads determined for each flow interval represents the daily total load of nutrients ($kg\ day^{-1}$). In this procedure, nutrient concentration measured in the middle of a flow interval is assumed to be representative for the particular interval.

Load for flow interval

The nutrient load for a flow interval is estimated according to the following mathematical expression:

$$l_m = Q_m C_{r+i_0}$$

where:

l_m = the nutrient load per flow interval in kg,
C_{r+i_0} = the nutrient concentration in $mg\ l^{-1}$ measured within a flow interval, where i_0 is the time of chemical sampling fixed in the middle of each of the 6-h flow intervals, $i = 3$.

Daily load

The daily nutrient load is estimated as follows:

$$L = \sum_{m=1}^{4} l_m$$

where:

L = the nutrient load expressed in $kg\ day^{-1}$.

RESULTS AND THEIR USE

Phosphorus flux in the Okanagan River reach at Penticton, B.C. is characterized by pronounced spatial and temporal variations as determined by the partial load method and by the flow interval method, respectively.

Figure 2 shows an example of the results obtained by the two methods used for the estimation of loads. Each point represented by a triangle symbol indicates daily mean load of total phosphorus based on sequential concentration measurements, taken at quarter-day intervals on each sampling day at one single point in the river channel. Each square symbol represents the cross-sectional load based on simultaneous concentration measurements taken at a channel cross-section on a particular day. The bar represents the 95% confidence interval about that load. If the bar is absent this indicates that the error of measurements is less than the size of the box.

Results obtained by the partial load and flow interval methods were compared graphically and

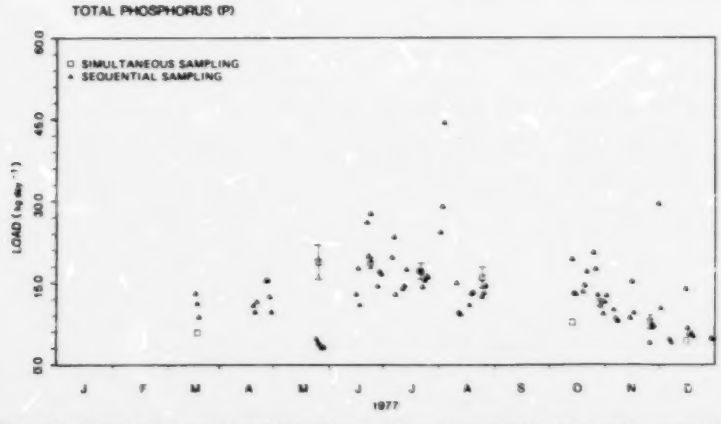

Fig. 2. Example of load estimates of total phosphorus derived from simultaneous and sequential sampling strategies in 1977. Okanagan River near the Penticton airport.

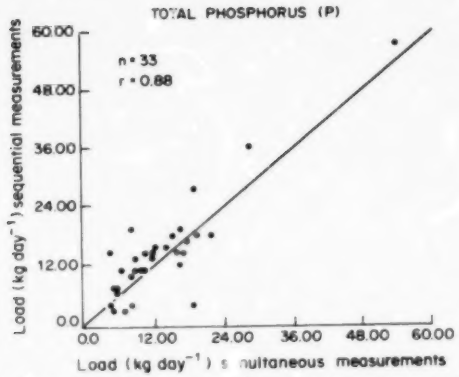

Fig. 3. Comparison of load estimates derived from simultaneous and sequential sampling strategies. Okanagan River, 1976–1978.

statistically (Zeman, 1982). There were some differences in the load estimate derived from these two methods. These differences were not statistically significant at the 95% level. Figure 3 shows the graphical comparison, number of observations and correlation coefficient of loads of total phosphorus derived from the two methods. The scatter of data points shows that load estimates obtained by flow interval method were higher in more cases than estimates derived from partial load method, i.e. there was a systematic bias superimposed on quasi-random fluctuations around the mean. Because of the significant correlation ($r = 0.88$), it would be possible to use the average of the estimates derived by these two methods. However, the flow interval method is more appropriate for obtaining time series records leading to the assessment of trends. The partial load method should be used when determination of variability of the load estimates is needed.

CONCLUSIONS

Phosphorus concentrations in the regulated river channel of the Okanagan River were sampled by simultaneous and sequential strategies. Because concentration-discharge relationship were not statistically significant at 95% level, phosphorus loads were then estimated in two ways (a) by partial load method and by (b) a flow interval method.

The partial load method, derived from simultaneous sampling, allowed calculation of confidence limits of load estimates. This sampling strategy revealed existence of very pronounced short range spatial heterogeneities of point concentration measurements (Zeman *et al.*, 1977) at the channel cross-sections. Consequently, the determination of nutrient loads based only on a single grab sampling procedure cannot provide a reliable estimate of the amounts of nutrients passing through a channel cross-section.

The flow interval method was derived from the sequential sampling strategy which provided time series records of single point concentration measurements. This method did not permit the calculation of confidence limits. Thus, the load estimates obtained by this method were compared with the results determined from the partial load method.

The average phosphorus load estimates were then calculated from the results obtained by these two methods. These data were used to determine annual trends in phosphorus loads. The estimates, with known precision, were used by water managers as a tool to assess the remedial actions undertaken to reduce phosphorus loads from the Penticton waste treatment plant to Skaha Lake.

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